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VAN. H. MANNING, DIRECTOR

EFFECTS OF MOISTURE ON THE SPONTANEOUS HEATING OF STORED COAL

BY

S. H. KATZ AND H. C. PORTER

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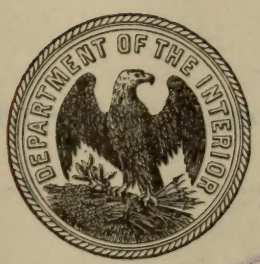

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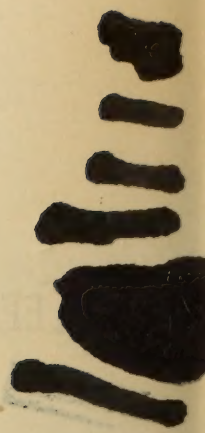

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EFFECTS OF MOISTURE ON THE SPONTANEOUS HEATING OF STORED COAL.

S. H. Katz and H. C. Porter.

INTRODUCTION.

Spontaneous fires in storage piles of bituminous coal have been the source of trouble and loss since the industrial utilization of coal began. In Europe the idea arose that spontaneous combustion is more liable to happen during wet weather than during dry. Statements favoring or opposing this idea have crept into the literature. Conflicting conclusions, based on experiment as well as opinions based on observations of various degrees of reliability, are given in most of the recorded discussions of the subject.

Because of the uncertainty of the effect of moisture and its seeming importance among the conditions that affect spontaneous combustion in stored coal, the work described in this paper was undertaken by the Bureau of Mines. The experiments showed that a coal from Illinois oxidized faster when dry, whereas a sample of Pittsburgh coal oxidized faster when moist. These discordant results and similarly inconsistent results from the observations of different investigators may be coupled with the fact that, under actual conditions of storing, both coal and air always contain a considerable amount of moisture. This has led to the conclusion that moisture in stored coal is not of practical importance as far as its chemical effects on oxidation are concerned. However, water may produce physical effects such as cooling through evaporation and reducing porosity by being held by capilarity in finely broken coal, and acting in these ways water may have far-reaching effects on spontaneous combustion.

PREVIOUS INVESTIGATIONS.

Although the coals used by different investigators have been of widely different origin, all have been subject to spontaneous combustion. Some of the more noteworthy investigations are mentioned below. Richters[a] found from laboratory experiments that with a German coking coal the dry coal absorbed oxygen much more rapidly than the moist.

[a] Richters, E., Ueber die Veränderungen welche die Steinkohlen beim Lagern an der Luft erleiden: Dingl. Poly. Jour., Bd. 195, 1870, pp. 315–331.

Fayol[a] made experimental investigations on a large and practical scale with French coals of various origin. These investigations were experimentally the most extensive and complete that were ever performed. Fayol concludes that the influence of wet weather was not marked enough to be observable.

Threlfall,[b] who was associated with English commissions and with the New South Wales commissions of 1896 and 1900 which investigated spontaneous fires in coal, has long been interested in this matter. His inquiries were from various sides and show breadth of vision. The second New South Wales commission found by experiment that in storing a large quantity of slack coal, thoroughly wet when stored, the water exerted a cooling effect as compared with similar coal stored without wetting. Threlfall writes interestingly of the prevalent idea of the effect of moisture on spontaneous combustion, as follows:

> There is no doubt a floating opinion among people accustomed to the handling of coal to the effect that moisture does increase the tendency to spontaneous combustion. In a letter to the English commission in 1876, Mr. Poole, inspector of mines, Nova Scotia, makes the following remark: "Heat has been observed in piles of slack coal that have been accumulated during the winter, when the season has been showery but not when it has been dry." This evidence is very direct and absolutely opposed to Fayol's experience, and a great deal of similar evidence was tendered to the English commission. For instance, out of 26 answers to questions as to the effect of moisture every reply was to the effect that moisture was a source of danger. An examination of the reported evidence shows that in every case (with the above exception) this was a matter of impression merely. Cross-examination of a number of witnesses before the New South Wales commission, who held this opinion, convinced me that it was in general held on very slender grounds; and two cases in which the rain had apparently increased the tendency of the coal to heat were otherwise explained.

In the presence of air and moisture pyrite readily oxidizes[c] and pyrite in coal has often been blamed for spontaneous combustion. Threlfall [d] showed that the oxidation of pyrite has much less effect in the heating of coal than the oxidation of the coal substance itself. He reviewed the work of previous investigators and commissions that investigated mine fires; all the evidence was against the idea.

On the other hand Parr and Kressman [e] found from laboratory experiments that actual wetting of an Illinois coal of high pyritic content increased the spontaneous heating in sizes less than one-eighth inch in diameter and in mixed sizes, but decreased the spontaneous heating in sizes of more than one-eighth inch diameter, and of high pyritic content, and decreased the heating in all sizes of coal of low pyritic content. They concluded that wetting was a source of danger for Illinois coals.

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a Fayol, Henri, Études sur l'altération et la combustion spontanée de la houille exposée à l'air: Bull. Soc. ind. min., t. 8, ser. 2, 1879, pp. 487-503.

b Threlfall, Richard, The spontaneous heating of coal, particularly during shipment: Jour. Soc. Chem. Ind., vol. 28, 1909, pp. 759-773.

c Parr, S. W., and Kressmann, F. W., The spontaneous combustion of coal. Bull. 46, Eng. Exp. Sta. University of Illinois, 1910, 87 pp.

d Threlfall, Richard, place quoted.

e Parr, S. W., and Kressman, F. W., place quoted.

Thus pyrite in the presence of moisture may be a contributing factor in causing spontaneous combustion in coal. However, as the experiments described in this paper dealt with the oxidation of the coal substance itself, which is usually the major factor, the pyrite factor is disregarded in the subsequent discussion.

Mahler[a] found that a coal of French origin in the presence of oxygen under pressure absorbed more when moist than when dry.

Likewise Graham[b] working in the laboratory with coal from an English mine found that moist coal oxidizes faster than dry. Graham presents his data and sums up the matter thus:

> These results show conclusively that the rate of oxidation of moist coal dust at 30° and 50° C., in a current of air saturated with moisture, is much greater than that for a portion of the same sample oxidized, when dry, the rates of oxidation in the two cases being on the average approximately as 1.5 to 1.

The various conclusions given above are inconsistent to say the least, and have left the problem almost as unsettled as when it was conceived. The authors have sought to reconcile the discrepancies.

METHOD OF EXPERIMENT.

Of two equal samples of the same coal, one was thoroughly desiccated and then placed in a closed bottle filled with air and containing a tube of phosphorous pentoxide to maintain complete dryness. The other sample, which contained moisture, was put in a similar bottle with a tube of water to keep the atmosphere saturated with water vapor. The bottles were placed side by side in a thermostat. With a few exceptions the thermostat operated only during the hours of work when the constant temperature was necessary to obtain the data. At night and on Sundays the temperature of the bath varied with that of the room.

As the oxygen was absorbed by the coal the pressure in the bottles fell. At regular intervals measurements were made, from which the pressures in the bottles were calculated. After 100 days the gas in contact with the coal was analyzed and the changes of the various gaseous constituents computed.

DESCRIPTION OF THE APPARATUS.

The exposed parts of the apparatus are shown in Plate I; *a* is an albarine stone tank; *b* is the motor and connected reducing gears for operating the stirrer; *c* is the switchboard for temperature control; and *d* and *e* are Haldane burettes inclosed in water jackets. The glass tubes, which connected to the burettes, lead to the submerged parts of the apparatus in the bath. Details of these parts are shown in figures 1 and 2.

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[a] Mahler, M. P., Expériences sur l'oxydation de la houille: Ann. des mines, Memoires, 11 ser., t. 4, 1913, pp. 163–198.

[b] Graham, J. I., The absorption of oxygen by coal: Coll. Guard., vol. 109, 1915, pp. 228–229.

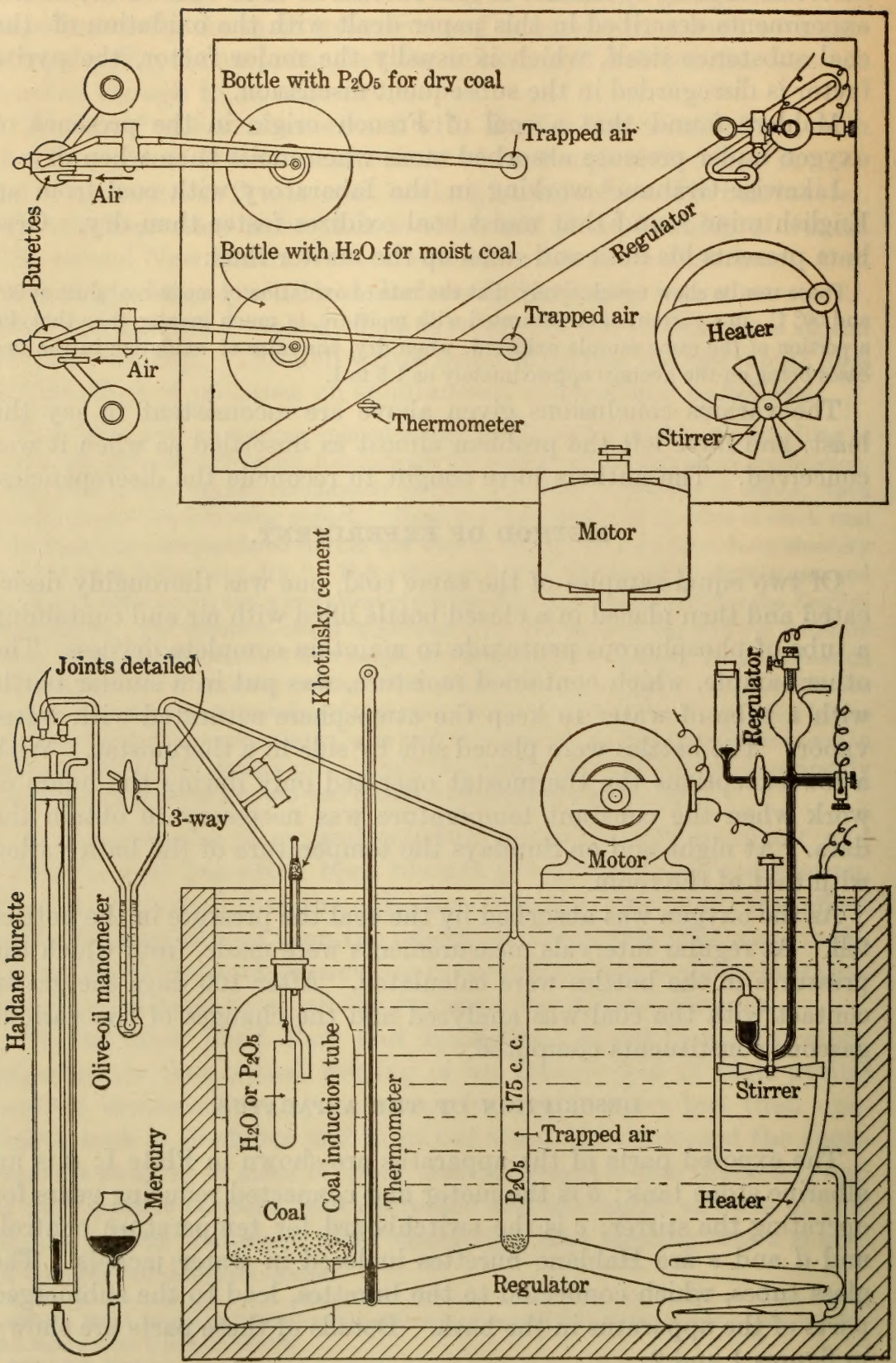
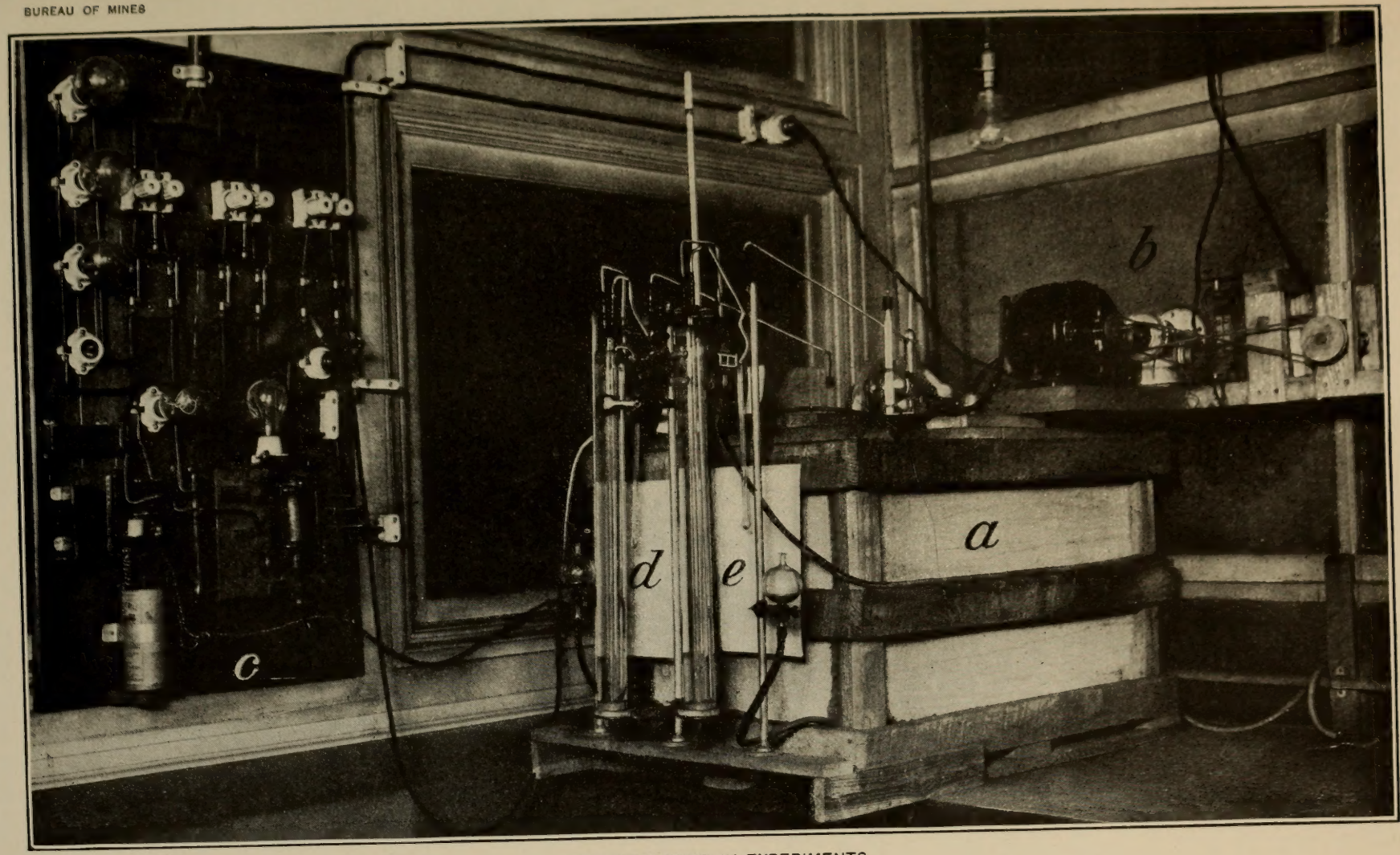


FIGURE 1.—Plan and elevation of apparatus.



APPARATUS USED IN EXPERIMENTS.

The thermostat, of the electrically heated and toluene-regulated type, operated with a high degree of constancy. A thermometer of the Beckman type showed a variation in temperature of not more than one thousandth of a degree from 25° when the room temperature was 20° C.

In the part of the apparatus used for the dry coal the volume of the gas in communication with the coal was 4,564 c. c. In the apparatus used for the moist coal the corresponding volume was 4,519 c. c.

METHOD OF DETERMINING PRESSURES.

By means of the gas formula $P_1 V_1 = P_2 V_2$ and from measurements made as described below the pressure of the gas over the coal was determined. When the experiment started, the manometer was level, the burette contained 20.000 c. c. of air, the temperature of the thermostat was 25° C., according to the thermometer used, and the air in all parts of the apparatus was at the recorded barometric pressure. Openings to the outside air were then closed. To determine the pressure of the atmosphere over the coal at 25° C. at any time thereafter the following operations were performed:

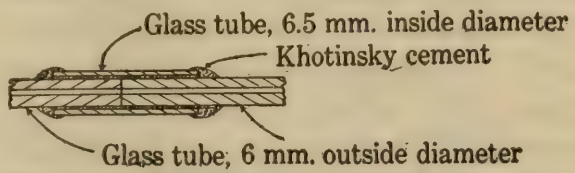


FIGURE 2.—Detail of joints marked "detailed" in figure 1.

The manometer first was made level; 20.000 c. c. (V_1) of gas at the bottle pressure (P_1), which was to be determined, was then fixed in the burette; next the volume (V_2) of this gas at the original known pressure (P_2) was determined by means of the manometer and trapped gas; from these data and with the gas equation the pressure of the gas over the coal was calculated.

Changes in the temperature of the room would tend to influence the determinations of the pressure by causing temperature changes of the gas in the burettes and exposed tubing. However, calculation showed that a change of 10° C. from normal room temperature would change the determined pressure by only 1 part in 20,000 parts, a negligible effect.

EXPERIMENT 1.

COAL USED.

The coal was from the Majestic mine at Du Quoin, Perry County, Ill., working the No. 6 or Herrin, coal.

PRELIMINARY TREATMENT.

In preparing the coal for experiment the sample for oxidation in dry air was desiccated in a vacuum with phosphorus pentoxide. The coal for oxidation in the presence of moisture was kept in a

small Mason jar with rubber gasket and air-tight cover. At this time it was exposed to the action of less than 400 c. c. of air originally present in the jar.

A chronological statement of the treatment given the coal before the experiment follows: This is made with especial reference to the exposure to air and consequent oxidation of the two coal samples preceding the actual experiment.

December 1, 1914. Three mine samples of coal collected in the standard manner adopted by the Bureau of Mines[a] were taken from different parts of the mine and sent to the Pittsburgh laboratory of the Bureau of Mines.

December 12, 1914. The samples were crushed to pass a quarter-inch screen and air-dried, and then the small quantity needed for analysis was taken out. The loss on air drying was 8.1 per cent. The analysis of this composite, air dry, was as follows:

Analysis of air-dry coal.

	Per cent.
Moisture	3.17
Volatile matter	35.27
Fixed carbon	53.20
Ash	8.36
Total	100.00
Sulphur	.82

Heat value, 6,985 calories.

The unused parts of the sample were kept in tin cans with screw tops.

February 10, 1915. The parts of the samples of one-eighth to one-fourth inch particles were crushed to pass entirely an 80-mesh sieve and the parts passing a 100-mesh sieve were rejected. A composite of equal parts of the 80 to 100 mesh coal was made from the three mine samples. Exactly 100 grams of the composite was placed in a desiccator, with phosphorus pentoxide, and the desiccator was evacuated to 3 mm. mercury pressure. The residue of 110 grams was put in a 1-pint jar and the jar hermetically sealed, some air thus being inclosed with the coal.

February 18, 23; March 1, 5, 8. The desiccator was opened and the dry coal was exposed to the air while being weighed in closed weighing bottles. It was then replaced in the desiccator and the desiccator evacuated.

On March 9, 100 grams of the original air-dried coal from the jar was put in the bottle for the thermostat. The desiccator was then opened and the coal weighed again. A gain of 0.002 per cent was found since the weighing four days previous, so the coal was thoroughly dry. It was then transferred to its bottle for the thermostat.

[a] Holmes, J. A., The sampling of coal in the mine: Tech. Paper 1, Bureau of Mines, 1911, 18 pp.

STARTING THE OXIDATION.

The first experiment differed from succeeding ones in that the coal was put into the bottles before they were in place in the thermostat. The bottles were then fixed in the thermostat, connections were made, the thermostat filled with water, heated to 25° C. and kept so for one hour to establish equilibrium of temperature and water vapor before connections to the outside air were closed. During these operations the coal was exposed to the air for three hours before the actual experiment began.

As indicated by extrapolating from the subsequent data, the moist coal did not absorb enough oxygen to affect appreciably the results afterwards obtained. But the desiccated coal absorbed oxygen rapidly when first exposed. It seems probable that this absorption may have been enough to cause a measurable decrease in the oxidation afterwards recorded, as compared with the oxidation in the moist sample during the same time.

EXPERIMENTAL RESULTS.

Several determinations of pressure were made daily for a period of 100 days. Table 1 gives a part of these records of time and pressure. Figure 3 shows the graph of time against pressure. From the data of Table 1, the average rates of oxidation in cubic centimeters of oxygen at standard conditions per 100 grams of coal have been calculated for intervals of time and are given in Table 2. Figure 4 is the graph of rate against time.

Analyses of the gas in contact with the coal at the end of the period of 100 days were made with a Haldane apparatus in the Bureau of Mines gas laboratory at Pittsburgh. Separate determinations of carbon monoxide and methane were made by G. B. Taylor by the method of iodine pentoxide and cupric oxide combustion. Table 3 presents the results of the analyses for all the experiments.

A statement of the changes in the various constituents of the gas calculated from the previous data is given in Table 4.

DISCUSSION OF RESULTS.

As shown in figure 4, the rate of oxidation of the moist sample was at first slow, in so far as decrease of pressure indicates oxidation. The rate gradually increased thereafter until it reached a maximum at about the twenty-fifth day of the experiment. From that time there was a small and gradual decrease in the rate until the experiment ended.

In marked contrast to this, the dry sample was oxidized at a manifoldly greater rate in the first week. During this period the rate declined rapidly; thereafter there was a more gradual decrease in the rate until the end.

Throughout the whole experiment the dry coal absorbed oxygen at a greater rate than the moist. Oxidation of the undried sample while the dry coal was being desiccated can not account for this; for if the coal had absorbed all the oxygen in the 400 c. c. of air to which it was exposed while in the Mason jar, it would still have absorbed insufficient oxygen to account for the difference found in the experiment.

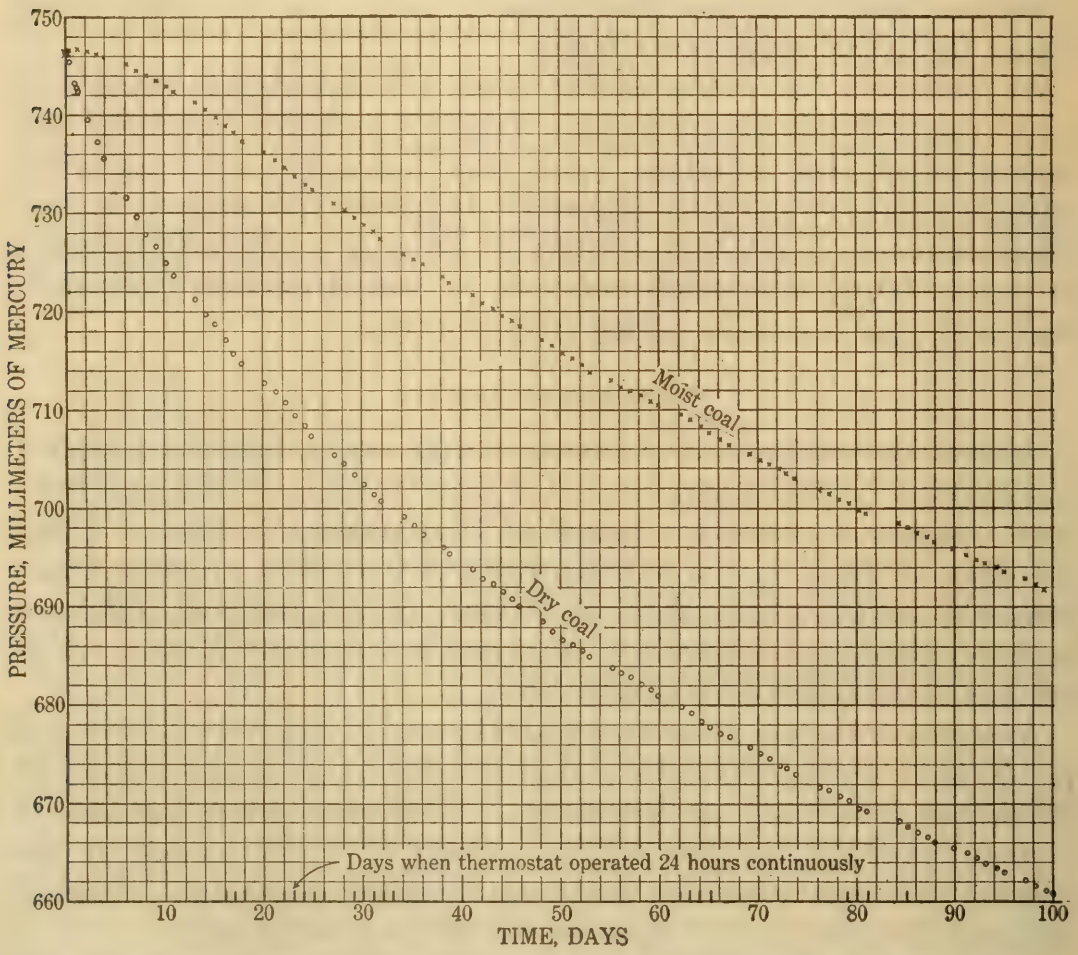


FIGURE 3.—Relation of change of pressure to time of exposure in experiment 1, with Illinois coal.

EXPERIMENT 2.

COAL USED.

The coal was from the Bureau of Mines experimental mine at Bruceton, Pa., in the Pittsburgh bed.

PRELIMINARY TREATMENT OF COAL SAMPLE.

The sample for oxidation in dry air was desiccated in vacuo by phosphorus pentoxide. The sample for oxidation in saturated air was kept in an atmosphere of 99.8 per cent nitrogen.

A chronological statement of the treatment the coal received before the experiment is given below.

May 25, 1915. Coal was mined and a lump weighing 7 kilos was selected for experiment.

June 2. The lump was crushed and a sample taken for analysis. The air-dry loss was 1.2 per cent; analysis of the air-dry coal gave these results:

Analysis of air-dry coal.	Per cent.
Moisture	1.68
Volatile matter	37.65
Fixed carbon	58.02
Ash	2.65
Total	100.00
Sulphur	.70

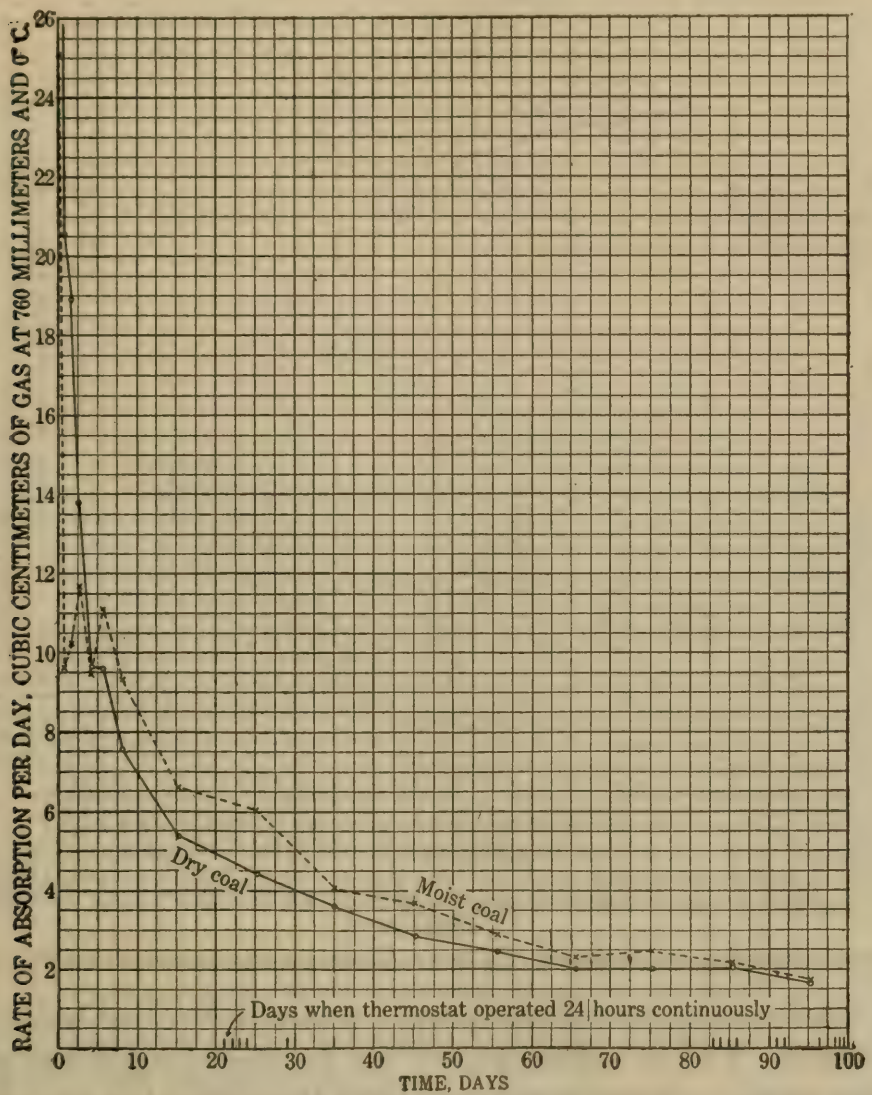


FIGURE 4.—Relation of rate of absorption to time of exposure in experiment 1, with Illinois coal.

The residue was ground and screened. Parts passing an 80-mesh sieve and lodging on a 100-mesh sieve were put in a small Mason jar with tight cover. The coal completely filled the jar. Two hours time was required for these operations.

June 3. One portion of 100 grams was put into a desiccator, the desiccator alternately evacuated and refilled several times with 99.8

per cent nitrogen and kept for experiment. Another portion of the same weight was put into a desiccator with phosphorus pentoxide. The desiccator was evacuated to 8 mm. pressure and so kept.

June 7. During the night the vacuum desiccator leaked; 110 mm. pressure of air was found. The pressure was reduced to 4 mm.

June 12, 15. The dried coal was weighed. A loss of less than 0.01 per cent was found between the two weighings.

STARTING THE OXIDATION.

June 23. The thermostat was completely arranged for the experiment. The temperature had stood at 25° C. for more than an hour.

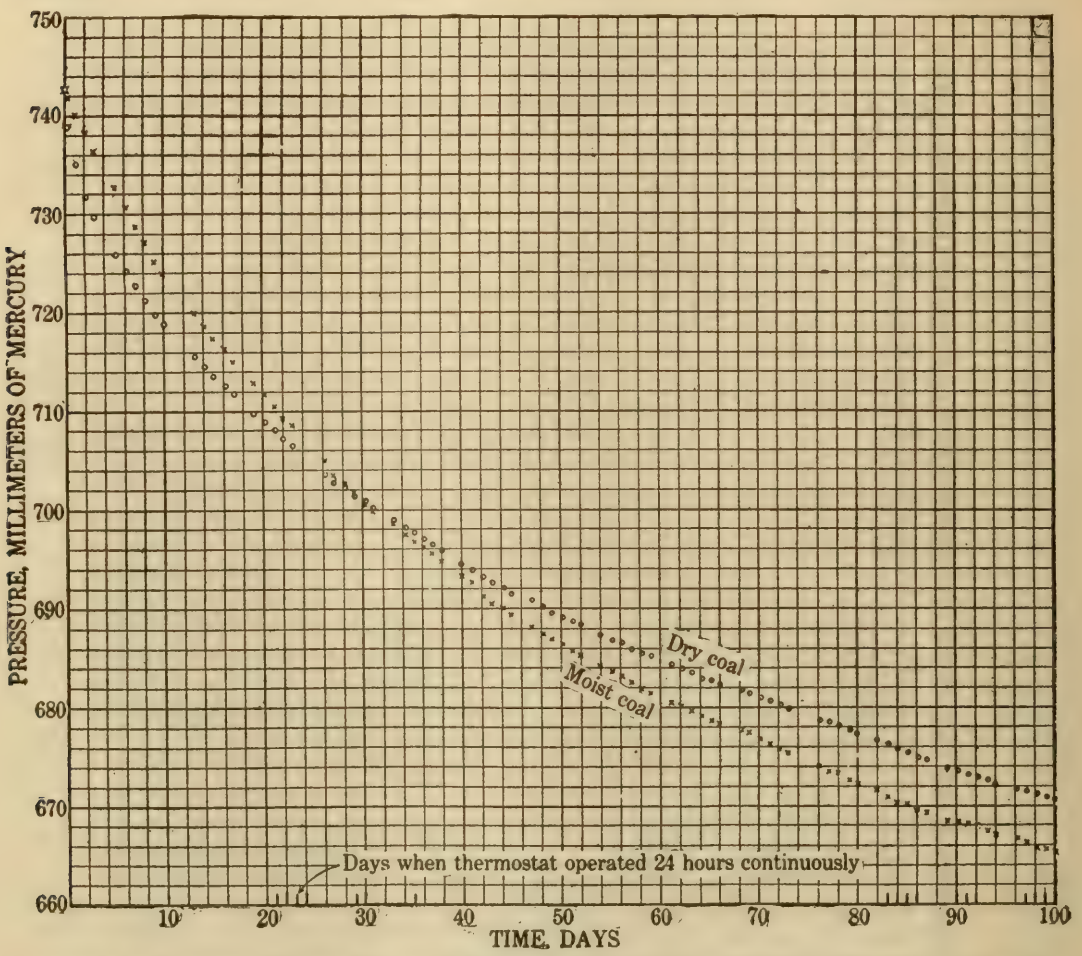


FIGURE 5.—Relation of change of pressure to time of exposure in experiment 2, with Pittsburgh coal.

First, the desiccated sample of coal was put into its bottle in the thermostat. Fifteen minutes later the undried sample was put into the thermostat. Twenty minutes later the apparatus was closed to the outside air and the experiment started.

EXPERIMENTAL RESULTS.

The results are given in Tables 1 to 4 as in the first experiment. Figure 5 is the graph of pressure against time; figure 6 is the graph of rate against time.

DISCUSSION OF RESULTS.

As in the case of the Illinois coal, the Pittsburgh coal which had been kept in vacuo during the drying process showed a very rapid absorption during the first few hours of exposure to the air. Thereafter the rate of absorption gradually decreased till after a week, when it became quite uniform and continued without marked change till the end of the 100-day period.

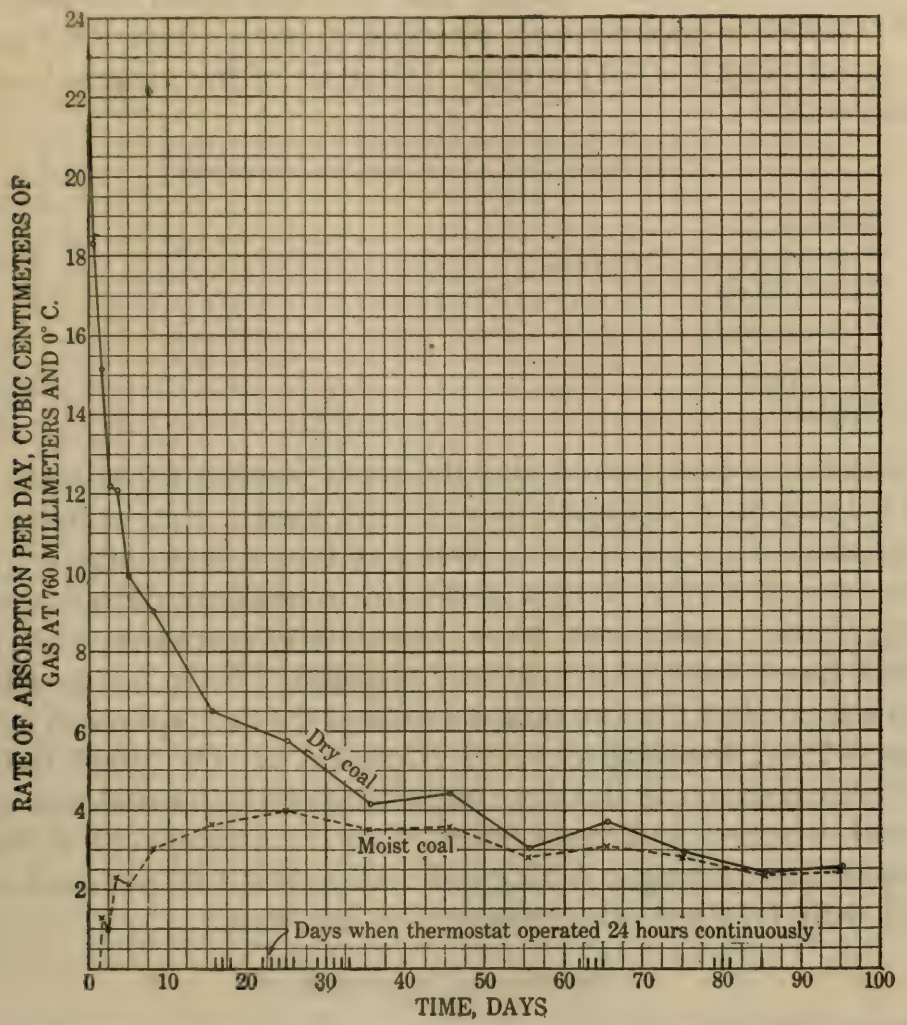


FIGURE 6.—Relation of rate of absorption to time of exposure in experiment 2, with Pittsburgh coal.

The decline in the rate of oxidation in the moist sample was more uniform during the entire period of the experiment. Compared with the rate of oxidation of the dry sample, that of the moist was greater after the first five days had passed.

EXPERIMENT 3.

COAL USED.

The coal was a large lump from the lot of Pittsburgh coal used in experiment 2.

PRELIMINARY TREATMENT OF COAL SAMPLE.

During the period of preparation both samples were kept in an atmosphere of nitrogen. The chronological statement of the treatment received by the two coals follows:

May 25, 1915. Coal was mined; a lump weighing about 10 kilos was selected and kept in lump form in the air of the laboratory.

August 11. The lump was chiseled to remove about one-half inch of the entire outer surface and only the inside was used. This was crushed to quarter-inch size and a sample taken for analysis. The air-dry loss was 0.5 per cent. Analysis of the air-dried coal gave these results:

Analysis of air-dried coal used in experiment 3.

	Per cent.
Moisture	1.74
Volatile matter	39.01
Fixed carbon	56.33
Ash	2.92
Total	100.00
Sulphur	.79

The residue was ground and the parts passing an 80-mesh screen and lodging on a 100-mesh screen were used. Two samples of 100 grams each were taken. One was put into a desiccator containing water, and the other into a desiccator containing phosphorus pentoxide. Both desiccators were alternately evacuated and refilled several times with 99.8 per cent nitrogen. Four hours after the lump was crushed the two samples were in the atmosphere of nitrogen.

August 31, September 4, 14, October 2. On these dates the desiccator containing the dry coal was opened, the coal was quickly covered, weighed, and again returned to the atmosphere of nitrogen. The total loss in weight during desiccation was 1.80 per cent as compared with 1.74 per cent moisture by analysis.

STARTING THE EXPERIMENT.

October 2. The thermostat, arranged for experiment, had stood at a temperature of 25° C. for 16 hours.

First the sample of coal in equilibrium with water vapor was put into the bottle in the thermostat. Ten minutes later the desiccated sample was put into the thermostat. Thirty-five minutes thereafter both samples in the thermostat were simultaneously closed from the outside air.

EXPERIMENTAL RESULTS.

The results are given in Tables 1 to 4. Figure 7 is the graph of pressure against time; figure 8 shows the rate of absorption against time.

DISCUSSION OF RESULTS.

On the first and third days of the experiment the rate of oxidation of the dry sample was greater than that of the moist coal. On the second, fourth, fifth days, and all times thereafter the moist coal oxidized more rapidly.

Comparison of the rates of oxidation of the dry samples used in the three experiments shows exceptionally high rates of oxidation during the first few days, as compared with the rates thereafter in the first and second experiments. In the third experiment no

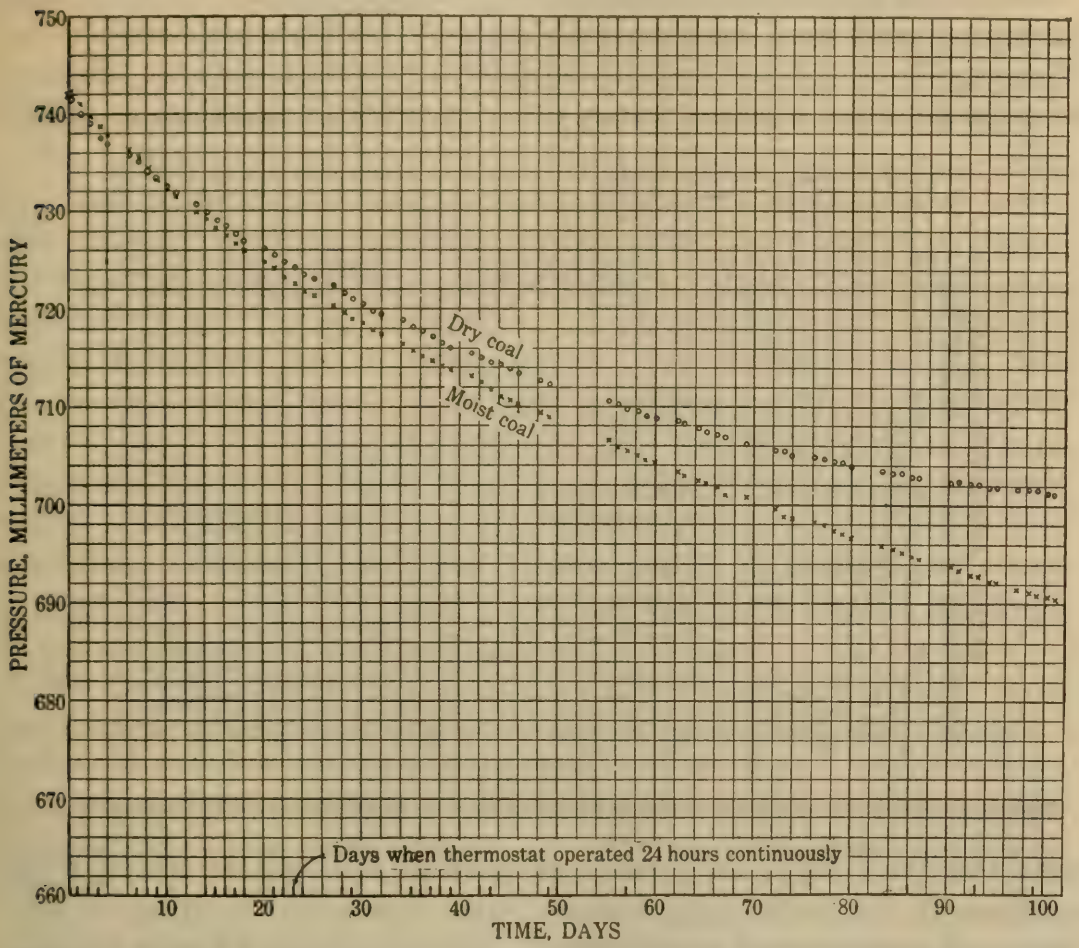


FIGURE 7.—Relation of change of pressure to time of exposure in experiment 3, with Pittsburgh coal.

such high rate was shown. Obviously the reason for this is that in the first and second experiment the desiccation was in vacuo, whereas in the third experiment it was in an atmosphere of nitrogen. Graham,[a] however, seems not to have found such an effect in his experiments.

CONCLUSIONS.

The experiments showed that with Illinois coal thoroughly dried the rate of oxidation at ordinary temperatures was greater than with a comparative sample of moist coal. On the other hand, a thor-

[a] Graham, J. I., The absorption of oxygen by coal: Coll. Guard., vol. 109, 1915, pp. 228–229.

oughly dried sample of Pittsburgh coal oxidized at a slower rate than a comparative moist sample of the same coal. This difference between the two coals probably explains the discrepancies in the observations of different experimenters. Richters [a] found that a German coal absorbed more oxygen when dry than when moist. Mahler [b] investigating a French coal, and Graham, [c] investigating an English coal, found that moist coal absorbed more oxygen than dry. Evidently the rates of oxidation of different coals are not affected uniformly by moisture.

The investigators named worked with small quantities of coal in the laboratory and used extreme conditions. Under actual conditions of storage both the coal and the air always contain moisture. Hence it seems doubtful whether water, other than the excess that actually

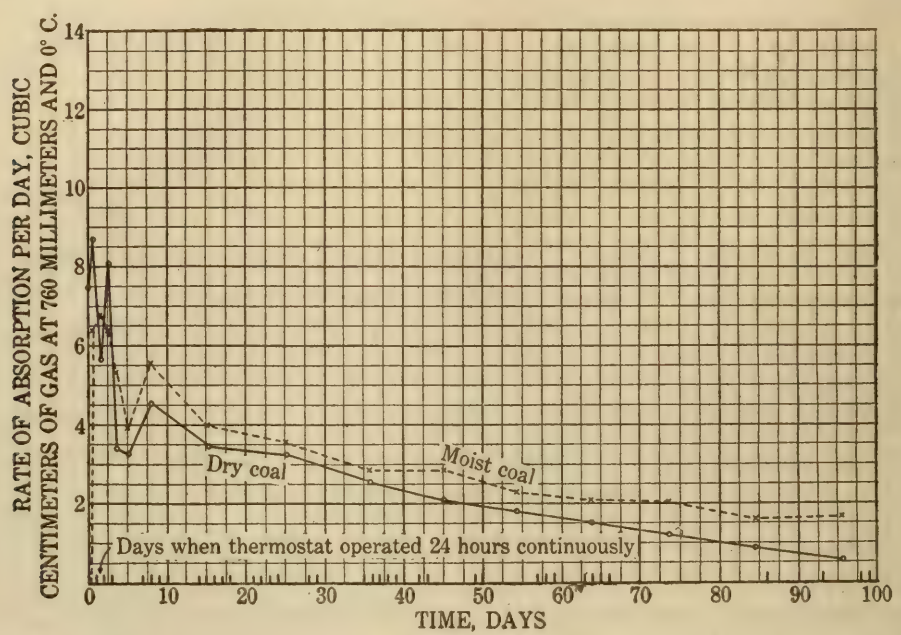


FIGURE 8.—Relation of rate of absorption to time of exposure in experiment 3, with Pittsburgh coal.

wets the coal, plays an important part in the rate at which coal oxidizes at the lower temperature, with consequent increase in the danger of spontaneous combustion. The experiments conducted on a working scale by Fayol [d]—who could find no influence of wet weather on spontaneous combustion—and the New South Wales commission [e]—which found that actual wetting of the coal produced a cooling effect during storage—tend to confirm this idea.

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[a] Richters, L., Ueber die Veränderungen welche die Steinkohlen beim Lagern an der Luft erleiden: Ding. poly. Jour., Bd. 195, 1870, pp. 315-331.

[b] Mahler, M. P., Expériences sur l'oxydation de la houille: Ann. des mines, Memoires, 11 ser., t. 4, 1913, pp. 163-198.

[c] Graham, J. I., The absorption of oxygen by coal: Coll. Guard., vol. 109, 1915, pp. 228-229.

[d] Fayol, Henri, Étude sur l'altération et la combustion spontanée de la houille exposée à l'air: Bull. Soc. ind. min., t. 8, sèr. 2, 1879, p. 487.

[e] Threlfall, Richard, Spontaneous heating of coal, particularly during shipment: Jour. Soc. Chem. Ind., vol. 28, 1909, pp. 759-773.

PRACTICAL CONSIDERATIONS.

However, the opinion among coal shippers and consumers that there is more danger of spontaneous combustion during warm, wet weather than during dry may have another basis, the physical changes[a] brought about by wetting the coal on the surface of a pile. Such wetting reduces the proportion of voids or open spaces in the mass. If the coal is divided into particles fine enough, the water will fill the voids completely and be held there by capillary attraction. Such a mass of coal and water on any part of a pile would block the passage of air at that place. As a result the conditions of ventilation in the pile before the wetting would be changed, so that, in some instances, the heat generated by the gradual oxidation of the coal would be retained until the temperature of ignition was reached.

For instance, in a pile of coal formed in the usual manner—with the fines at the top because of the rolling down of the larger particles—there would be a mass overlain with an impervious cover through the wetting of the outside surface. This cover would prevent air circulating by convection. Under such conditions oxygen would diffuse, as the coal absorbed it, from the lower parts of the pile to the covered part. The heat produced would be retained in the pile, and the temperature of the coal would increase at a rate dependent on the rate of oxidation alone; ignition temperature would readily be reached, and a spontaneous fire produced. The conditions described have been approximated to a degree in many storage piles of coal. In those piles moisture had a decided influence in the production of spontaneous fire.

The only recommendations of practical import to be made as a result of the matters considered in this paper is to prevent the segregation of the fine coal in building a pile for storage. This has been proposed before as a means of reducing the danger of spontaneous combustion.[b] The consideration of moisture now gives it further support.

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[a] A similar change is expressed by Porter, J. B., Weathering of coal; An investigation of the coals of Canada: Canada Department of Mines, 1915, 194 pp.

[b] Threlfall, Richard, The spontaneous heating of coal particularly during shipment: Jour. Soc. Chem. Ind., vol. 28, 1909, pp. 759-773; Porter, H. C., and Ovitz, F. K., Deterioration and spontaneous heating of coal in storage: Tech. Paper 16, Bureau of Mines, 1912, 14 pp.; Katz, S. H., The diffusion of oxygen through stored coal: Tech. Paper 170, Bureau of Mines, 1917, 47 pp.

TABLE 1.—*Time and pressure.*

EXPERIMENT NO. 1.

Days.	Pressure (mm. of mercury).		Days.	Pressure (mm. of mercury).		Days.	Pressure (mm. of mercury).		Days.	Pressure (mm. of mercury).	
	Dry.	Moist.		Dry.	Moist.		Dry.	Moist.		Dry.	Moist.
1	2	3	4	5	6	7	8	9	10	11	12
0.0000	746.30	746.30	7.1681	729.62	744.62	38.9931	695.25	722.94	71.1681	674.58	704.51
.0035	746.41	.....	8.1819	727.98	744.06	41.1750	693.98	721.67	72.1688	673.98	704.02
.0049	.....	746.30	9.1660	726.49	743.58	42.1618	692.94	720.93	73.0278	673.50	703.65
.0236	746.30	.....	10.1625	724.92	742.94	43.1681	692.23	720.33	73.9958	672.94	703.01
.0264	.....	746.37	10.9993	723.65	742.34	44.1750	691.45	719.69	76.1715	671.81	702.01
.0493	746.11	.....	13.1674	721.30	741.23	45.1750	690.78	719.06	77.1708	671.30	701.52
.0514	.....	746.45	14.1737	719.84	740.48	45.9931	690.07	718.54	78.1708	670.81	701.00
.1132	745.85	.....	15.1688	718.65	739.92	48.1667	688.46	717.19	79.1736	670.21	700.48
.1153	.....	746.71	16.1743	717.16	738.95	49.1715	687.65	716.52	80.1674	669.62	699.99
.1229	745.85	.....	17.1625	715.81	738.24	50.1701	686.68	715.74	80.9958	669.24	699.58
.1250	.....	746.71	17.9903	714.73	737.34	51.1701	686.12	715.18	84.1695	668.13	698.46
.1438	745.74	.....	20.1632	712.83	736.15	52.1701	685.59	714.51	85.1729	667.60	698.01
.1458	.....	746.60	21.1708	711.93	735.44	52.9924	684.95	713.91	86.1722	667.04	697.42
.1694	745.59	746.67	22.1729	710.59	734.66	55.1681	683.95	713.09	87.1701	666.63	697.04
.8826	743.28	746.30[a]	23.1681	709.36	733.69	56.1715	683.27	712.60	87.9958	666.15	696.52
.8903	743.24	746.37	24.1743	708.24	732.90	57.1694	682.79	711.97	89.9889	665.44	695.89
.9208	743.02	746.41	24.9944	707.34	732.23	58.1688	682.04	711.49	91.1688	664.84	695.25
.9569	742.90	746.56	27.1667	705.51	730.96	59.1167	681.48	710.93	92.1701	664.36	694.81
.9896	742.72	746.75	28.1840	704.58	730.29	59.9938	680.92	710.44	93.1688	663.91	694.43
1.0257	742.72	746.60	29.1750	703.46	729.51	62.1688	679.92	709.51	94.1688	663.42	694.06
1.0486	742.61	746.67	30.1715	702.38	728.76	63.1688	679.21	708.95	94.9896	663.05	693.65
1.1076	742.47	746.64	31.1743	701.45	728.02	64.1771	678.31	708.13	97.1722	662.08	692.86
1.1771	742.23	746.71	31.9938	700.78	727.31	65.0285	677.86	707.49	98.1688	661.59	692.12
2.1326	739.58	746.49	34.1715	699.02	725.78	66.1688	677.12	706.93	98.9111	.....	691.82
3.1778	737.27	746.30	35.1667	698.12	725.33	66.9972	676.63	706.34	99.1597	661.07	.....
3.9917	735.48	745.96	36.1715	697.27	724.62	69.1681	675.63	705.55	99.8778	660.85	.....
6.1681	731.56	745.14	38.1667	695.92	723.50	70.1681	675.03	704.88			

EXPERIMENT NO. 2.

0.0000	742.70	742.70	1.0472	735.64	.....	31.0243	700.18	699.96	66.0340	682.24	678.31
.0035	741.96	.....	1.0486	.....	740.25	33.1736	698.88	698.51	68.1701	681.80	677.68
.0049	.....	742.40	1.1070	735.46	.....	34.2243	698.18	697.54	69.0451	681.39	677.42
.0069	741.51	.....	1.1090	.....	740.17	35.1777	697.58	696.76	70.1736	680.98	676.75
.0090	.....	742.25	1.1410	735.31	.....	36.1777	696.95	696.21	71.1785	680.65	676.23
.0111	741.14	.....	1.1438	.....	740.14	37.0076	696.47	695.65	72.1917	680.24	675.78
.0132	.....	741.99	1.1819	735.16	.....	38.0222	695.91	694.80	73.0236	679.94	675.37
.0153	740.81	.....	1.1840	.....	740.10	40.0028	694.54	693.31	76.1688	678.83	674.00
.0174	.....	741.96	2.1875	731.71	738.21	41.1750	693.94	692.68	77.0472	678.49	673.63
.0236	740.29	.....	3.0208	729.63	736.42	42.1771	693.20	691.27	78.0465	678.16	673.33
.0257	.....	741.99	5.1826	725.84	732.67	43.1840	692.57	690.41	79.1833	677.68	672.59
.0333	740.10	.....	6.1819	724.10	730.63	44.1861	692.20	690.01	80.0674	677.34	672.25
.0354	.....	741.99	7.1792	722.61	728.66	45.0278	691.57	689.37	82.0028	676.71	671.66
.0701	739.84	.....	8.1764	721.16	727.14	47.1847	690.71	688.11	83.0479	676.23	671.03
.0722	.....	742.11	9.1715	719.82	725.14	48.1840	690.15	687.52	84.0507	675.82	670.29
.0854	739.77	.....	10.0354	718.82	724.06	49 1910	689.63	687.00	85.0500	675.45	670.29
.0875	.....	742.07	13.1757	715.52	719.94	50.1708	689.23	686.48	86.1813	674.89	669.51
.1125	739.47	.....	14.1764	714.55	718.60	51.1813	688.74	685.81	87.0069	674.67	669.25
.1146	.....	742.07	15.1861	713.47	717.34	52.0215	688.41	685.22	89.1500	673.89	668.30
.1722	738.99	.....	16.1875	712.62	716.22	54.0493	687.44	684.18	90.1882	673.59	668.28
.1743	.....	741.96	17.0361	711.73	715.03	55.1736	686.85	683.58	91.1958	673.18	668.13
.1854	738.88	.....	19.0514	709.98	712.99	56.1715	686.51	683.17	92.1701	672.96	667.95
.1875	.....	741.85	20.1806	708.98	711.88	57.1757	685.99	682.47	93.1833	672.59	667.39
.9285	735.61	.....	21.1785	708.05	710.62	58.1764	685.55	681.95	94.0083	672.14	667.02
.9313	.....	739.77[a]	22.0111	707.27	709.32	59.0111	685.18	681.43	96.1695	671.77	666.76
.9701	735.94	.....	23.0528	706.42	708.54	61.1681	684.32	680.57	97.1917	671.48	666.20
.9729	.....	740.29	26.1778	703.71	704.86	62.1681	683.95	680.13	98.1806	671.25	665.87
.9847	735.72	.....	27.1806	702.78	703.45	63.1778	683.47	679.61	99.1875	670.92	665.46
.9868	.....	740.29	28.1799	702.19	702.48	64.1756	683.06	679.20	100.0694	670.70	.....
1.0181	735.68	.....	29.1750	701.41	701.70	65.1833	682.91	678.83	100.1333	.....	665.20
1.0201	.....	740.36	30.2174	700.92	700.66						

[a] Vapor pressure low from cooling at night; soon reaches equilibrium.

TABLE 1.—*Time and pressure*—Continued.

EXPERIMENT NO. 3.

Days.	Pressure (mm. of mercury).		Days.	Pressure (mm. of mercury).		Days.	Pressure (mm. of mercury).		Days.	Pressure (mm. of mercury).	
	Dry.	Moist.		Dry.	Moist.		Dry.	Moist.		Dry.	Moist.
1	2	3	4	5	6	7	8	9	10	11	12
0.0000	741.90	741.90	3.1806	737.56	738.64	34.1983	718.72	716.38	69.1861	706.29	700.72
.0014	741.90	.....	4.0243	737.04	737.82	35.1979	718.16	715.79	72.2042	705.62	699.54
.0028	.....	741.97	6.1979	735.74	736.26	36.2000	717.75	715.19	73.1493	705.40	698.94
.0139	741.90	.....	7.1847	734.89	735.26	37.1903	717.16	714.67	74.0250	705.18	698.72
.0146	.....	742.09	8.1917	734.11	734.18	38.1792	716.60	714.08	76.1865	704.77	698.16
.0271	741.64	.....	9.1896	733.29	733.26	39.0271	716.19	713.71	77.1986	704.69	697.72
.0285	.....	742.27	10.1986	732.44	732.18	41.2042	715.49	712.93	78.1882	704.43	697.39
.0563	741.64	.....	11.0250	731.85	731.40	42.1889	715.15	712.34	79.1483	704.10	697.02
.0576	.....	742.27	13.1910	730.55	729.96	43.2056	714.56	711.70	80.0028	703.95	696.72
.1333	741.64	.....	14.1861	729.84	729.10	44.1979	714.15	711.11	83.1854	703.43	695.94
.1354	.....	742.27	15.1826	729.07	728.21	45.0569	713.82	710.70	84.1986	703.32	695.53
.1917	741.64	.....	16.1785	728.43	727.43	46.0160	713.34	710.15	85.1806	703.21	695.16
.1938	.....	742.23	17.2076	727.69	726.54	48.1993	712.78	709.40	86.1986	702.91	694.86
.8583	740.53	.....	18.0306	727.06	725.95	49.1829	712.34	708.77	86.9618	702.73	694.49
.8596	.....	741.53[a]	20.2083	726.17	724.84	55.1875	710.55	706.44	90.2090	702.28	693.79
.9500	740.42	.....	21.1861	725.50	724.06	56.2056	710.11	705.92	91.2083	702.32	693.42
.9521	.....	741.27	22.1910	724.87	723.35	57.1889	709.78	705.40	92.2063	702.28	692.97
1.0215	740.42	.....	23.1986	724.17	722.54	58.2083	709.52	705.06	93.2028	702.13	692.86
1.0236	.....	741.23	24.1875	723.58	721.87	59.2125	709.03	704.58	94.2047	701.95	692.38
1.0514	740.34	.....	25.0271	723.06	721.31	60.0250	708.81	704.36	95.0118	701.87	692.16
1.0535	.....	741.20	27.1993	722.24	720.31	62.2104	708.40	703.36	97.2000	701.84	691.56
1.1403	740.34	.....	28.1829	721.61	719.68	62.8785	708.22	703.06	98.2063	701.76	691.12
1.1424	.....	741.16	29.1854	721.05	718.94	64.2007	707.77	702.54	99.1695	701.69	690 82
1.1972	740.05	.....	30.1979	720.38	718.42	65.2000	707.36	702.13	100.2076	701.36	690.71
1.1993	.....	741.05	31.1806	719.98	717.83	66.1938	707.14	701.85	100.9604	701.24	.....
1.2014	740.05	.....	32.0236	719.53	717.38	67.0299	706.77	700.91	101.0194	.....	690.41
2.2056	739.01	739.79									

[a] Thermostat operated during night. Water vapor equilibrium existed in moist bottle.

TABLE 2.—*Calculated rates of change a day.*

EXPERIMENT No. 1.

Time, days.			Pressure, mm. of mercury.				Volume c. c. (760 mm., 0°).			
Total elapsed.	Difference elapsed.	Average time.	Dry coal.	Moist coal.	Change in dry.	Change in moist.	Average rate of change a day.		Average rate of change a day.	
							Dry.	Moist.	Dry.	Moist.
1	2	3	4	5	6	7	8	9	10	11
0.0000	.....	.....	746.3	746.3	.....	.....	.....	.....	.....	.....
.1694	0.1694	0.0847	745.59	746.67	−0.71	+0.37	−4.2	+2.2	−23	+12
1.1771	1.0077	.6733	742.23	746.71	−3.36	+ .04	−3.33	+ .04	−18.3	+ .2
2.1326	.9555	1.6549	739.58	746.49	−2.65	− .22	−2.77	− .23	−15.2	− 1.3
3.1778	1.0452	2.6552	737.27	746.30	−2.31	− .19	−2.21	− .18	−12.2	− .98
3.9917	.8139	3.5848	735.48	745.96	1.79	.34	2.20	.42	−12.1	2.3
6.1681	2.1764	5.0799	731.56	745.14	3.92	.82	1.80	.38	9.91	2.1
10.9993	4.8312	8.5837	723.65	742.34	7.91	2.80	1.64	.58	9.02	3.2
20.1632	9.1639	15.5813	712.83	736.15	10.82	6.19	1.18	.676	6.50	3.68
30.1715	10.0083	25.1674	702.38	728.76	10.45	7.39	1.045	.739	5.75	4.03
41.1750	11.0035	35.6733	693.98	721.67	8.40	7.09	.763	.644	4.20	3.51
50.1701	8.9951	45.6726	686.68	715.74	7.30	5.93	.812	.659	4.47	3.59
62.1688	11.9987	56.1695	679.92	709.51	6.76	6.23	.564	.519	3.10	2.83
70.1681	7.9993	66.1685	675.03	704.88	4.89	4.63	.676	.579	3.72	3.15
80.1674	9.9993	75.1678	669.62	699.99	5.41	4.89	.541	.489	2.98	2.67
91.1688	11.0014	85.5681	664.84	695.25	4.78	4.74	.434	.431	2.39	2.35
98.9111	7.7423	95.0400	.....	691.82	.....	3.43	.....	.443	.....	2.41
99.8778	8.7090	95.5233	660.85	.....	3.99	.....	.458	.....	2.52	.....

TABLE 2.—*Calculated rates of change a day*—Continued.

EXPERIMENT No. 2.

Time, days.			Pressure, mm. of mercury.						Volume c. c. (760 mm., 0°).	
Total elapsed.	Difference elapsed.	Average time.	Dry coal.	Moist coal.	Change in dry.	Change in moist.	Average rate of change a day.		Average rate of change a day.	
							Dry.	Moist.	Dry.	Moist.
1	2	3	4	5	6	7	8	9	10	11
0.0000	.....	.....	742.7	742.7	.....	.....	.....	.....	.....	.....
.1854	0.1854	0.0927	738.88	741.85	3.82	0.85	20.6	4.6	113	25.1
1.1819	.9965	.6842	735.16	740.10	3.72	1.75	3.73	1.76	20.53	9.59
2.1875	1.0056	1.6847	731.71	738.21	3.45	1.89	3.43	1.88	18.88	10.25
3.0208	.8333	2.6042	729.62	736.42	2.08	1.79	2.50	2.15	13.76	11.71
5.1826	2.1618	4.1017	725.84	732.67	3.79	3.75	1.754	1.735	9.66	9.46
6.1819	.9993	5.6823	724.10	730.63	1.74	2.04	1.742	2.042	9.59	11.13
10.0354	3.8535	8.1087	718.82	724.06	5.28	6.57	1.370	1.705	7.54	9.29
20.1806	10.1452	15.1080	708.98	711.88	9.84	12.18	.970	1.201	5.34	6.54
30.2174	10.0368	25.1990	700.92	700.66	8.06	11.22	.803	1.118	4.42	6.09
40.0028	9.7854	35.1101	694.54	693.31	6.38	7.35	.652	.752	3.59	4.10
50.1708	10.1680	45.0868	689.23	686.48	5.31	6.83	.522	.672	2.87	3.66
61.1681	10.9973	55.6695	684.32	680.57	4.91	5.91	.446	.537	2.45	2.93
70.1736	9.0055	65.6709	680.98	676.75	3.34	3.82	.371	.424	2.04	2.31
80.0674	9.8938	75.1205	677.34	672.25	3.64	4.50	.368	.455	2.03	2.48
90.1882	10.1208	85.1278	673.59	668.28	3.75	3.97	.370	.392	2.04	2.14
100.0028	9.8146	95.0955	670.70	665.20	2.89	3.08	.295	.314	1.62	1.71

EXPERIMENT No. 3.

0.0000	.....	.....	741.9	741.9	.....	.....	.....	.....	.....	.....
.1917	0.1917	0.0959	741.64	742.23	−0.26	+0.33	−1.36	1.72	−7.48	+9.37
1.1993	1.0076	.6955	740.05	741.05	−1.59	−1.18	−1.58	−1.17	−8.70	−6.38
2.2056	1.0063	1.7025	739.01	739.79	−1.04	−1.26	1.03	−1.25	−5.67	−6.81
3.1806	.9850	2.6981	737.56	738.64	1.45	1.15	1.47	1.17	8.09	6.38
4.0243	.8437	3.6025	737.04	737.82	.52	.82	.616	.972	3.39	5.30
6.1979	2.1736	5.1111	735.74	736.26	1.30	1.56	.598	.718	3.29	3.91
10.1986	4.0007	8.1983	732.44	732.18	3.30	4.08	.824	1.019	4.53	5.55
20.2083	10.0097	15.2035	726.17	724.84	6.27	7.34	.627	.734	3.45	4.00
30.1979	9.8896	25.1531	720.38	718.42	5.79	6.42	.586	.649	3.22	3.54
41.2042	11.0063	35.7011	715.49	712.93	4.89	5.49	.465	.522	2.56	2.85
49.1829	7.9887	45.1986	712.34	708.77	3.15	4.16	.394	.521	2.17	2.84
59.2125	10.0296	54.1977	709.03	704.58	3.31	4.19	.330	.418	1.82	2.28
69.1861	9.9736	63.7093	706.29	700.72	2.74	3.86	.275	.387	1.51	2.11
79.1483	9.9622	73.6672	704.10	697.02	2.19	3.70	.220	.372	1.21	2.03
90.2090	11.0607	84.6787	702.28	693.79	1.82	3.23	.165	.292	.908	1.59
100.9604	10.7514	95.5847	701.24	.....	1.04	.....	.097	.....	.534	.....
101.0194	10.8104	95.6142	.....	690.41	.....	3.38	.....	.313	.....	1.71

TABLE 3.—*Analyses of gas from bottles containing coal.*

Experiment No.	Kind of coal.	Oxidation, moist or dry.	Per cent by volume.					Remarks on preliminary treatment of coal.
			Carbon dioxide.	Carbon monoxide.	Methane.	Oxygen.	Nitrogen.	
1	Illinois....	Dry.....	0.51	0.32	0.00	9.30	89.87	Analyzed with Haldane apparatus.
1	...do.....	...do.....	.....	.294	.005	.....	.....	Analyzed by I_2O_5 and CuO method.
1	...do.....	...do.....	.51	.294	.005	9.30	89.89	Accepted analysis. Coal was desiccated in vacuo with P_2O_5.
1	...do.....	Moist...	1.20	.16	.01	11.10	87.53	Analyzed with Haldane apparatus.
1	...do.....	...do.....	.....	.178	.009	.....	.....	Analyzed by I_2O_5 and CuO method.
1	...do.....	...do.....	1.20	.178	.009	11.10	87.51	Accepted analysis. Coal was kept in small sealed container in atmosphere of air during desiccation of dry sample.
2	Pittsburgh	Dry.....	.31	.12	.00	12.16	87.41	Coal desiccated in vacuo with P_2O_5.
2	...do.....	Moist...	.58	.16	.00	10.14	89.12	Coal kept in nitrogen during drying of other sample.
3	...do.....	Dry.....	.29	.16	.00	14.92	84.63	Coal dried in nitrogen with P_2O_5.
3	...do.....	Moist...	.93	.15	.02	13.60	85.30	Coal kept in nitrogen with free water during drying of other sample.

TABLE 4.—*Observed changes in gas.*

Experiment No.	Kind of coal.	Oxidation, moist or dry.	Time.	Volume, c. c. at 760 mm. and 0° C.					
				Carbon dioxide.	Carbon monoxide.	Methane.	Oxygen.	Nitrogen.	Total.
1	Illinois....	Dry.....	Start.....	1.2	0.0	0.00	859.3	3,245	4,106
			End.....	18.5	10.7	.18	338.1	3,268	3,636
			Change in volume.....	+17.3	+10.7	+.18	−521.2	+23	−470
1	...do.....	Moist...	Start.....	1.2	.0	.00	824.0	3,112	3,937
			End.....	43.7	6.5	.33	404.1	3,186	3,640
			Change in volume.....	+42.5	+6.5	+.33	−419.9	+74	−297
2	Pittsburgh	Dry.....	Start.....	1.2	.0	.0	855.2	3,230	4,086
			End.....	11.4	4.4	.0	448.7	3,225	3,690
			Change in volume.....	+10.2	+4.4	.0	−406.5	−5	−396
2	...do.....	Moist...	Start.....	1.2	.0	.0	819.9	3,096	3,917
			End.....	20.3	5.6	.0	354.4	3,115	3,495
			Change in volume.....	+19.1	+5.6	.0	−465.5	+19	−422
3	...do.....	Dry.....	Start.....	1.2	.0	.0	854.3	3,226	4,082
			End.....	11.2	6.2	.0	575.6	3,265	3,858
			Change in volume.....	+10.0	+6.2	.0	−278.7	+39	−224
3	...do.....	Moist...	Start.....	1.2	.0	.0	819.0	3,098	3,913
			End.....	33.8	5.4	.7	494.0	3,099	3,633
			Change in volume.....	+32.6	+5.4	+.7	−325.0	+6	−280

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